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Status and Nutrient Requirement Index of Patchouli on Inceptisols of Aceh, Indonesia

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Abstract

This study assessed macronutrient (N, P, K, Ca, Mg) and micronutrient (Fe) status and determined the nutrient requirement index for patchouli (*Pogostemon cablin Benth*) cultivated on the Inceptisols in Lhoong District, Aceh Besar (1325.26 ha). Topsoil samples (0 - 20 cm) were collected from 26 composite points representing six land units, stratified by slope (0% - 8% and 8% - 15%) and land use. Soil analyses included pH, organic C, total N, available P, exchangeable K, Ca, Mg, and available Fe. Results indicated acidic to slightly acidic soils (pH 5.50 - 5.80) with variable organic C (1.92% - 6.40%). Nutrient status varied across land units, with N, P, Mg, and Fe identified as limiting nutrients, while K and Ca were generally sufficient. Suboptimal cation ratios indicated potential nutrient imbalance. These findings highlight the need for site-specific nutrient management. It is recommended to prioritize N, P, Mg, and Fe inputs, combined with organic amendments and liming to improve soil pH, enhance nutrient availability, and sustain patchouli productivity.

Keywords

Inceptisols, Soil Quality, Nutrient Status, Patchouli

1. Introduction

Patchouli (*Pogostemon cablin* Benth.) is one of the most widely cultivated aromatic crops for the production of essential oil. The species is adaptable to both lowland and highland agroecosystems. Indonesia harbors several patchouli types; however, Aceh patchouli is the most recognized and extensively cultivated by farmers. This cultivar is the national export standard due to its distinctive aroma and relatively high oil yield, ranging from 2.5% to 3% [1], while its chemical composition exhibits considerable variability in response to environmental and management factors [2].

In Indonesia, patchouli is cultivated across multiple regions, with Aceh Province particularly renowned for its production. Cultivation in this region has a long history and, over the past decade, the commodity has regained strategic importance for both local governments and farming communities due to its significant contribution to farmers' income [3]. Strong market demand coupled with favorable price conditions has further stimulated farmers' interest in improving crop management practices. At present, several regencies located in the western and southern regions of Aceh, namely Aceh Besar, Aceh Jaya, Aceh Barat, Aceh Barat Daya, and Aceh Selatan, constitute the primary production centers. However, yields vary considerably, depending on soil quality and fertility status, cultivated varieties, and agronomic practices [4].

Aceh Besar Regency represents one of the key development areas, particularly in Lhoong District, covering approximately 14,903 ha. Nevertheless, not all of this area is suitable for patchouli cultivation due to biophysical constraints, including slope gradients, soil characteristics, and water availability or rainfall distribution [5]. Patchouli cultivation in this area has experienced a revival during the last three years following a previous decline. The development zone is characterized by three soil orders: Inceptisols, Entisols, and Ultisols. Inceptisols and Ultisols generally dominate gently sloping to undulating landscapes (8% - 25% slope), whereas Entisols are mainly found in mountainous and steep terrains (25% - 65%) and, to a lesser extent, in flat valley bottoms. Inceptisols constitute one of the most extensive soil orders utilized for upland agriculture, including patchouli cultivation. Nationally, Inceptisols cover approximately 70.52 million ha, representing 37.5% of Indonesia's land area [6]. Several studies indicate that Inceptisols are moderately suitable for patchouli, although certain soil-related constraints require management interventions [7]-[11].

High patchouli productivity can be achieved when cultivation is conducted on suitable land with appropriate management practices, particularly where soil constraints are adequately addressed, as is often the case in Inceptisols. Common soil quality limitations include variable texture (ranging from coarse to fine), low inherent fertility [8] [12], low organic matter content, low cation exchange capacity (CEC), and low base saturation. These soils are generally slightly acidic to acidic and often exhibit limited availability of essential nutrients such as N, P, K, Ca, and Mg, as well as low potential K reserves. Previous studies conducted in patchouli-growing areas of Aceh indicate that yields remain below the national production standard [4]. Furthermore, [13] reported nutrient deficiency symptoms in patchouli leaves cultivated on Inceptisols and Ultisols in Aceh.

Optimal patchouli growth is strongly influenced by the availability of macro- and micronutrients in the soil. According to [14], macronutrients are required in relatively large quantities (0.1% - 5% of plant dry weight) and include C, H, O, N, S, P, K, Ca, and Mg. Micronutrients are required in much smaller amounts (<0.025%) but are equally essential for plant growth and physiological functions;

these include Fe, Mn, Cu, Zn, Mo, B, and Cl. Ensuring adequate macro- and micronutrient availability in patchouli-growing soils is crucial to prevent both nutrient deficiency and toxicity. Nutrient imbalance, whether in the form of deficiency or excess, can adversely affect plant growth and development [15]. Nutrient disorders may arise not only from limited nutrient supply but also from nutrient imbalance and dynamics within the soil system [12], as well as from cation selectivity and competition within the exchange complex [16] [17].

Nutrient selectivity and plant nutritional status were assessed using the Diagnosis and Recommendation Integrated System (DRIS), a method that evaluates nutrient balance and generates nutrient requirement indices. This study assessed soil nutrient status and determined nutrient requirement indices for macronutrients (N, P, K, Ca, and Mg) and the micronutrient Fe in patchouli cultivation areas established on Inceptisols in Aceh Besar Regency, Indonesia.

2. Materials and Methods

2.1. Study Area and Period

This study was conducted in the patchouli development area of Lhoong District, Aceh Besar Regency, Indonesia. Soil sample analyses were carried out at the Soil Chemistry Laboratory, Faculty of Agriculture, Universitas Syiah Kuala. The research was undertaken over one year, from November 2022 to December 2023, during the rainy season.

2.2. Field and Laboratory Equipment

Field equipment included a Global Positioning System (GPS) device for georeferencing sampling points, hoes, soil augers, plastic sampling bags, rubber bands, a compass, and measuring tape. Laboratory instruments comprised a soil grinder, drying oven, pH meter, digital balance, mechanical shaker, nitrogen digestion and distillation unit, burette, Erlenmeyer flasks, graduated cylinders, filter papers, pipettes, titrator, spectrophotometer, and Atomic Absorption Spectrophotometer (AAS).

2.3. Reagents and Materials

Chemical reagents used for soil analyses included sodium hydroxide (NaOH), potassium dichromate ($K_2Cr_2O_7$), sulfuric acid (H_2SO_4), hydrogen peroxide (H_2O_2), Bray II extracting solution, 1 *N* ammonium acetate (NH_4OAc) at pH 7, potassium chloride (KCl), ferrous sulfate ($FeSO_4$), hydrochloric acid (HCl), and distilled water. Additional materials consisted of the research site map (patchouli development area of Lhoong District), composite soil samples, plastic sampling bags, and labeling materials. All chemical reagents were of analytical grade and used according to standard soil laboratory procedures.

2.4. Data Collection and Techniques

This study employed a descriptive research design using a survey method, consisting of four main stages: site preparation, soil sampling, laboratory analysis, and data processing. A preliminary survey was conducted to gather baseline information on the research area through direct field observations of existing and prospective patchouli cultivation sites. The surveyed locations comprised individually or family-managed farmland owned by local farmers. Information collected during the preliminary survey included site characteristics such as vegetation cover, slope gradient, and soil order. Based on these attributes, land unit (LU) maps were developed through an overlay analysis of thematic maps. Observation points were subsequently established within each delineated land unit. The overlay analysis resulted in the identification of six (6) land units, differentiated according to two slope classes (0% - 8% and 8% - 15%), three land-use types (secondary forest, upland agriculture/dryland farming, and shrubland), and one soil order (Inceptisols, classified as Eutrudepts). Spatial analysis using Geographic Information Systems (GIS) confirmed the delineation of these six land units. The spatial distribution of sampling points and land units is presented in **Figure 1**, while detailed descriptions of each land unit are provided in **Table 1**.

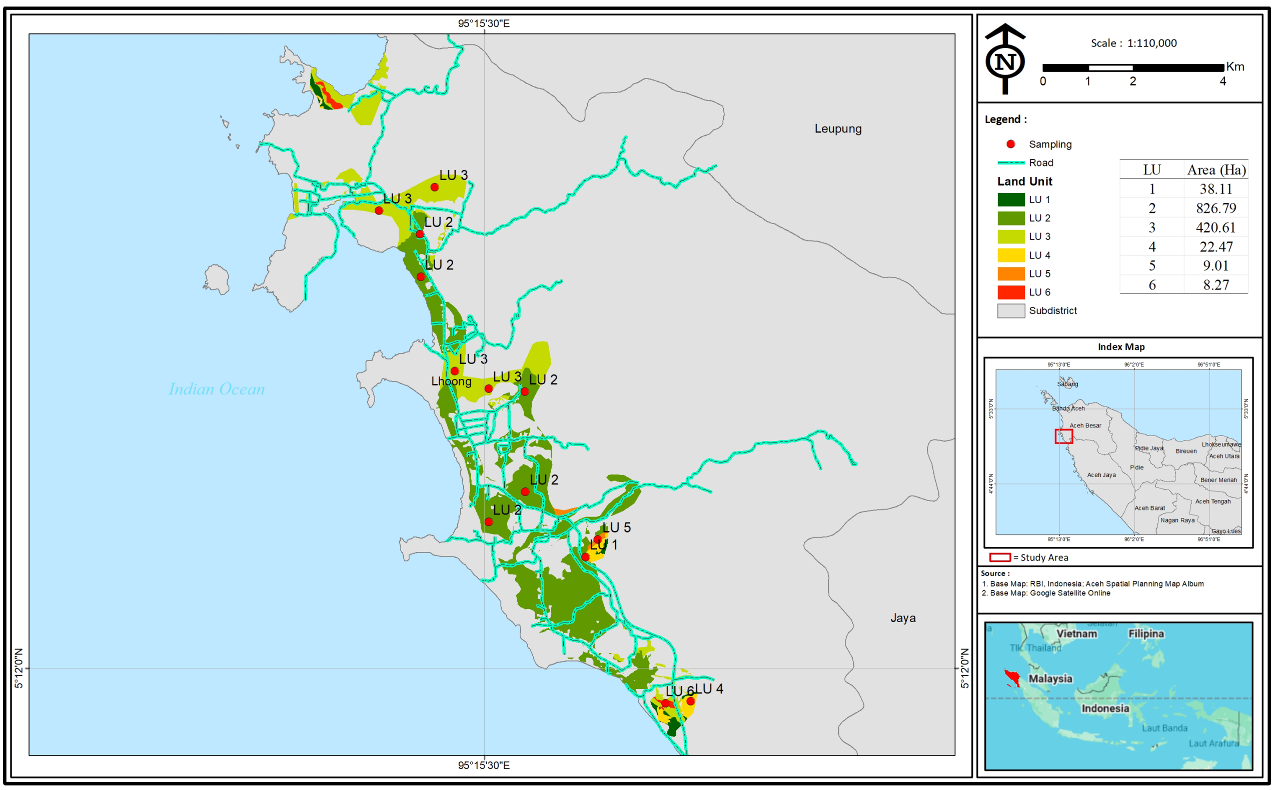

Figure 1. Map of the study area and soil sampling points in Lhoong District, Aceh Besar Regency, Indonesia.

Soil samples were collected using a purposive sampling method within each land unit. Composite samples were obtained from the topsoil layer (0 - 20 cm depth). As each land unit varied in area size, sampling intensity was determined at one composite sample per maximum area of 100 ha. For land units covering less than 100 ha, at least two samples were collected. A total of 104 soil samples were collected throughout the study area and then composited into 26 subsamples representing six land units. Soil samples were collected using a soil auger, placed in labeled plastic bags, and transported to the laboratory for analysis of selected physical and chemical soil properties, including macro- and micronutrient contents. Before laboratory analysis, the soil samples were air-dried for approximately two weeks, gently crushed using a porcelain mortar and pestle, and subsequently sieved through 0.5 mm and 2.0 mm mesh sieves according to standard soil preparation procedures.

Table 1. Description of land units at the soil sampling sites.

No. LU	Slope	Land use	Area (ha)	Number of samples
1	0% - 8%	Secondary forest (SF)	38.11	2
2	0% - 8%	Dryland Agriculture (DA)	826.79	10
3	0% - 8%	Schrub (SB)	420.61	8
4	8% - 15%	Secondary forest (SF)	22.47	2
5	8% - 15%	Dryland Agriculture (DA)	9.01	2
6	8% - 15%	Schrub (SB)	8.27	2
		Total of Areas	1325.26	26

2.5. Soil Analysis

Soil analyses were conducted at the Soil Chemistry Laboratory, Faculty of Agriculture, Universitas Syiah Kuala. The observed parameters included macronutrients (N, P, K, Ca, and Mg) and the micronutrient Fe. Supporting soil chemical properties were also analyzed, including soil pH, organic C, and soil moisture content. Soil pH was measured electrometrically using a pH meter at a soil-to-solution ratio of 1:2.5 (soil: distilled water or KCl). Soil organic carbon was determined using the Walkley and Black method. The soil samples were oxidized with H_2SO_4 and $K_2Cr_2O_7$, followed by titration with $FeSO_4$ solution. Total nitrogen (N) was analyzed using the Kjeldahl method. Soil samples were digested with concentrated sulfuric acid until a clear solution was obtained. Sodium hydroxide (NaOH) was then added for distillation, and the released ammonia (NH_3) was captured in boric acid (H_3BO_3) solution and subsequently titrated with standardized 0.01 M HCl.

Available phosphorus (P) was extracted using Bray I solution (0.3 N NH_4F + 0.25 N HCl), and P concentration in the extract was measured using a UV-1800 spectrophotometer at a wavelength of 693 nm. Exchangeable K, Ca, and Mg were extracted using 1 *N* ammonium acetate (NH_4OAc) at pH 7. Concentrations of Ca and Mg in the extracts were determined titrimetrically using EDTA solution with Eriochrome Black T (EBT) and Calcon indicators. Available Fe was extracted using 1 N NH_4OAc buffered at pH 4.8, and its concentration in the extract was measured spectrophotometrically at a wavelength of 510 nm. Soil chemical properties were classified according to the criteria established by the Indonesian Soil Research Institute [18], as presented in Table 2.

Table 2. Criteria for the evaluation of soil chemical parameters according to [18].

Parameters of Analysis		Very low	Low	Medium	High	Very high
Organic C or SOC (%)		<1.0	1.0 - 2.0	2.0 - 3.0	3.0 - 5.0	>5.0
Total N (%)		<0.1	0.1 - 0.2	0.2 - 0.5	0.51 - 0.75	>0.75
Available P ($mg \cdot kg^{-1}$)		<4.4	4.4 - 6.5	6.6 - 10.9	11 - 15.3	>15.3
Exchangeable K ($cmol(+) \cdot kg^{-1}$)		<0.1	0.1 - 0.2	0.3 - 0.5	0.6 - 1.0	>1.0
Exchangeable Ca ($cmol(+) \cdot kg^{-1}$)		<2.0	2.0 - 5.0	6.0 - 10	11 - 20	>20
Exchangeable Mg ($cmol(+) \cdot kg^{-1}$)		<0.4	0.4 - 1.0	1.1 - 2.0	2.1 - 8.0	>8.0
Available Fe ($mg \cdot kg^{-1}$)		<0.1	0.1 - 0.2	0.3 - 0.5	0.6 - 1.0	>1.0
	Very acid	Acid	Slightly acid	Neutral	Slightly alkalis	Alkalis
pH (H_2O)	<4.5	4.5 - 5.5	5.6 - 6.5	6.6 - 7.5	7.6 - 8.5	>8.5

SOC = soil organic matter.

3. Results and Discussion

3.1. Soil Chemical Characteristics and Nutrient Availability

3.1.1. pH-H_2O, SOC, Total N, and Available P

Soil chemical properties presented in Table 3 indicate that soil pH (H_2O) in the patchouli (*Pogostemon cablin*) cultivation area in Lhoong, Aceh Besar, ranged from 5.50 to 5.80, indicating acidic to slightly acidic conditions. Two land units (LU 1 and LU 2) exhibited acidic soil pH, while four land units (LU 3 to LU 6) were classified as slightly acidic. Soil pH values within the acidic to slightly acidic range are among the factors that may inhibit plant growth, including patchouli (*Pogostemon cablin*). Variations in slope and land-use type were not determining factors of soil pH, as all soils within the study area belong to the Inceptisols order. Field survey results revealed that the Inceptisols in the study area have undergone moderate weathering, as indicated by the presence of a Bw (cambic) horizon underlying an A epipedon (umbric) [5]. The acidic to slightly acidic soil conditions are attributed to the ongoing decomposition of organic matter, producing organic acids that consequently lower soil pH [19]. Weathering of organic materials produces organic and inorganic acids, further increasing soil acidity [20].

Furthermore, soil organic carbon (SOC) content varied considerably among land units, ranging from 1.92% to 6.40%, corresponding to low to very high categories (Table 3). Low SOC content was observed only in LU 6, while very high SOC content was found in LU 1. The remaining land units exhibited moderate SOC levels. These analytical results indicate that, in general, the patchouli development areas within the study region possess moderate to high levels of organic matter, suggesting relatively good soil quality [21]. Soil organic carbon reflects the amount of soil organic matter and plays a crucial role in enhancing soil fertility from physical, chemical, and biological perspectives, as it serves as a source of plant nutrients and energy for most soil organisms. Organic matter also contributes to increasing carbon availability in the soil [22] [23]. The very high SOC content observed at the research site is highly favorable for patchouli cultivation. This finding is consistent with [24], who state that soil organic matter, expressed as organic carbon, should be maintained above 2% to sustain and improve soil chemical, physical, and biological fertility. Maintaining adequate organic matter levels is essential to prevent declines over time due to decomposition and mineralization processes.

Table 3. Soil pH, soil organic carbon, total N, and available P in each land unit of Inceptisols in Aceh Besar.

LU	Slope (%)	Land use type	pH H_2O	SOC (%)	Total N (%)	Available P ($mg \cdot kg^{-1}$)
1	0 - 8	Secondary forest (Sf)	5.50 ± 0.04^{a}	6.40 ± 0.02^{vh}	0.59 ± 0.01^{h}	5.27 ± 0.01^{l}
2	0 - 8	Dryland farming (Df)	5.50 ± 0.01^{a}	2.27 ± 0.01^{m}	0.20 ± 0.00^{l}	3.84 ± 0.01^{vl}
3	0 - 8	Shrubs (Sb)	5.60 ± 0.02^{sa}	2.65 ± 0.01^{m}	0.21 ± 0.00^{m}	3.12 ± 0.02^{vl}
4	8 - 15	Secondary forest (Sf)	5.70 ± 0.04^{sa}	2.90 ± 0.02^{m}	0.31 ± 0.01^{m}	4.82 ± 0.03^{l}
5	8 - 15	Dryland farming (Df)	5.80 ± 0.03^{sa}	2.41 ± 0.03^{m}	0.21 ± 0.01^{m}	5.05 ± 0.04^{l}
6	8 - 15	Shrubs (Sb)	5.70 ± 0.03^{sa}	1.92 ± 0.02^{l}	0.29 ± 0.01^{m}	3.95 ± 0.03^{vl}

Remark: a = acid; sa = slightly acid; vl = very low; l = low; m = medium; h = high; vh = very high; LU = land unit; SOC = soil organic carbon.

Table 3 also shows that total soil nitrogen (N) at the study site ranged from low to high (0.20% - 0.59%). Low total N content was observed in LU 2, a dryland agricultural area with a slope of 0% - 8%. This condition is likely associated with acidic soil pH, potentially inhibiting optimal microbial development [25]. Under acidic soil conditions, microbial activity is suppressed, leading to reduced nitrogen fixation. Nitrogen is a primary macronutrient essential for plant growth. The low total N content in these Inceptisols may also be attributed to leaching, as nitrogen is highly susceptible to loss from the soil, particularly as nitrate (NO_3^-), readily leached, and ammonia (NH_3), prone to volatilization into the atmosphere [26]. Although LU 2 exhibited low total N content, the patchouli development area in Lhoong, Aceh Besar generally showed moderate N levels, with LU 1 classified as high in total N. These data indicate that total soil N status is relatively consistent with SOC status. Organic matter contains proteins (organic N) that, during decomposition, are broken down by microorganisms into amino acids and subsequently transformed into ammonium (NH_4^+) and nitrate (NO_3^-), both soluble in the soil [27]. Based on the results of total N analysis, it can be concluded that the patchouli development area generally provides adequate nitrogen availability to support patchouli growth.

Phosphorus (P) is an essential nutrient required for plant growth and is classified as a primary macronutrient. Plants absorb P from the soil in the form of phosphate ions, predominantly as $H_2PO_4^-$ in acidic soils and as HPO_4^{2-} in alkaline soils. Phosphorus is relatively stable in the soil; therefore, losses due to leaching rarely occur [28]. **Table 3** indicates that available P levels at the study site fall within the very low to low categories. Very low available P was observed in LU 2, LU 3, and LU 6, while low available P was recorded in LU 1, LU 4, and LU 5. Low available P content is a common characteristic of Inceptisols, as these soils generally exhibit relatively low fertility levels. Although phosphorus is required by plants in substantial amounts, its availability in soil is often lower than that of other nutrients, primarily due to P fixation processes. Low available P levels may also result from limited decomposition of soil P sources or from the presence of sparingly soluble mineral P forms [29]. Based on the soil analysis results, it can be concluded that the patchouli cultivation area remains deficient in available phosphorus to adequately support optimal plant growth. A clearer comparison of selected soil chemical properties, such as pH, soil organic carbon, total nitrogen, and available phosphorus, among land units is presented in **Figure 2**.

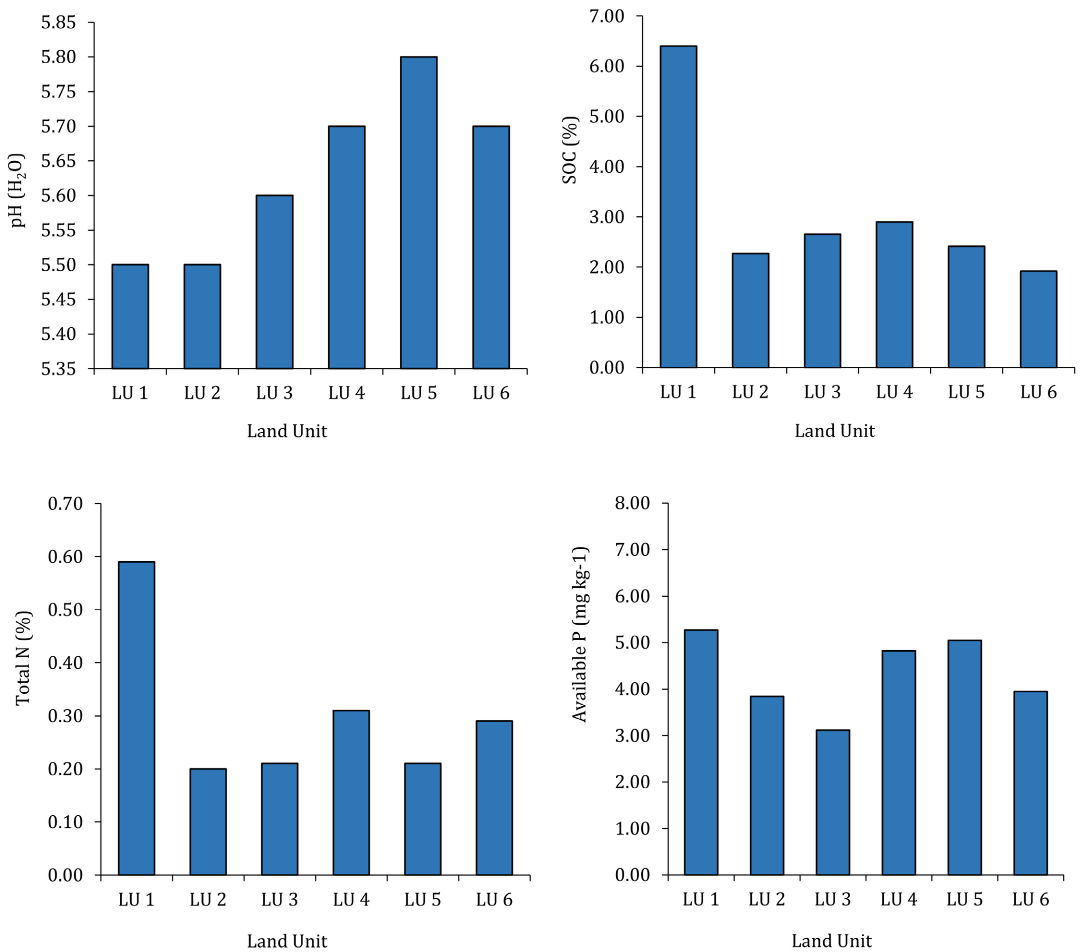

Figure 2. Comparison of soil pH, soil organic carbon (SOC), total N, and available P across land units in the Inceptisols of Aceh Besar.

In general, the chemical characteristics of soils in the patchouli development area of Lhoong Sub-district, Aceh Besar, reveal several constraints, as not all land units have reached optimal criteria. For example, soil pH in LU 1 and LU 2 falls below the lower threshold (dashed line) and is classified as acidic, whereas LU 3 to LU 6 exhibit pH values above 5.5, indicating optimal conditions for patchouli cultivation [7]. Furthermore, soil organic carbon (SOC) and total N levels are low across most of the area, with only LU 1 classified as high. This indicates that these two parameters act as limiting factors for patchouli growth, as organic matter and total nitrogen not only improve soil quality but also serve as important nutrient sources, particularly nitrogen [11]. **Figure 2** also demonstrates that available P content in nearly all land units remains at the lower threshold (low category), indicating that phosphorus availability constitutes another limiting factor for patchouli cultivation. Therefore, appropriate soil amendments are required in the management of the Inceptisols for patchouli cultivation in the Lhoong Sub-district, Aceh Besar, to improve overall soil quality.

3.1.2. Nutrient Cations: K, Ca, Mg, and Fe

Laboratory analysis of exchangeable K, Ca, Mg, and Fe across each land unit in the patchouli development area (**Table 4**) indicates that exchangeable potassium (K-exch) values ranged from 1.01 to 2.11 cmol(+)·kg^{-1} across all land units. These values are classified as very high, as they exceed 1.0 cmol(+)·kg^{-1}. This range suggests that exchangeable K levels in the study area are sufficient to meet the potassium requirements of patchouli. Exchangeable K refers to the fraction of potassium held on the soil exchange complex that is readily available for plant uptake, as it can easily dissolve into the soil solution as K^+ ions. Plants absorb potassium in cationic form, primarily from exchangeable and dissolved K in the soil. Potassium availability is influenced by soil organic matter content and potassium fixation processes [30].

Although potassium is an essential nutrient for plant growth, excessively high K levels in soil may lead to nutrient imbalances, particularly by inhibiting the uptake of calcium (Ca) and magnesium (Mg) [31]. Based on the potassium requirements of patchouli, the study area can therefore be considered to have a very favorable level of K availability [32].

Table 4. Exchangeable K, Ca, and Mg, and available Fe in each land unit of the Inceptisols in Lhoong, Aceh Besar.

LU	Slope (%)	Land use type	Exch. K	Exch. Ca	Exch. Mg	Available Fe
1	0 - 8	Secondary forest (Sf)	1.37 ± 0.01^{vh}	21.7 ± 0.07^{vh}	0.80 ± 0.01^{l}	0.33 ± 0.01^{vl}
2	0 - 8	Dryland farming (Df)	1.21 ± 0.01^{vh}	3.30 ± 0.02^{l}	0.80 ± 0.01^{l}	0.28 ± 0.00^{vl}
3	0 - 8	Shrubs (Sb)	1.47 ± 0.01^{vh}	10.1 ± 0.05^{h}	1.30 ± 0.02^{m}	0.22 ± 0.01^{vl}
4	8 - 15	Secondary forest (Sf)	1.01 ± 0.01^{vh}	15.1 ± 0.06^{h}	0.80 ± 0.01^{l}	0.21 ± 0.00^{vl}
5	8 - 15	Dryland farming (Df)	1.74 ± 0.02^{vh}	10.9 ± 0.04^{h}	1.50 ± 0.02^{m}	0.23 ± 0.01^{vl}
6	8 - 15	Shrubs (Sb)	2.11 ± 0.02^{vh}	5.80 ± 0.02^{m}	0.70 ± 0.01^{l}	0.48 ± 0.02^{vl}

Remark: a = acid; sa = slightly acid; vl = very low; l = low; m = medium; h = high; vh = very high; LU = land unit; Exch. = exchangeable.

Table 4 also shows that exchangeable calcium (Exch. Ca) in the patchouli development area varies considerably, ranging from 3.30 to 21.7 cmol(+)·kg^{-1} and falls within the low to very high categories. The lowest Ca-exch content was recorded in LU 2, while the highest was observed in LU 1; the remaining land units were classified as moderate. The land unit with low exchangeable Ca is likely associated with acidic soil pH and elevated H^+ activity in the soil [33]. Calcium is a secondary macronutrient absorbed by plants in the form of Ca^{2+}. Calcium in soils primarily derives from parent material and is commonly associated with sand and silt fractions, occurring in minerals such as anorthite, limestone, pyroxene, amphibole, and calcite [34]. However, its concentration varies widely depending on soil type and the degree of soil development.

Some Inceptisols with acidic pH are typically characterized by low concentrations of base cations such as Ca^{2+}, Mg^{2+}, and K^+, as well as low base saturation [35]. In the present study, exchangeable Ca levels classified as moderate, high, or very high do not pose constraints for patchouli cultivation, as they meet nutrient sufficiency criteria [36]. Adequate calcium availability is essential for patchouli, as Ca plays a crucial role in stimulating root hair formation, strengthening stems, and promoting seed development. Conversely, calcium-deficient soils may lead to chlorosis in leaves [13]. Young buds may die due to poor root development and may exhibit abnormal growth. Newly formed leaves may show discoloration, and localized tissue necrosis may occur on the leaf blades.

The analysis of exchangeable magnesium (Exch. Mg) presented in Table 4 indicates that its content ranged from 0.80 to 1.30 cmol(+)·kg^{-1}, corresponding to low to moderate categories. Low Exch. Mg levels were observed in LU 1, LU 2, LU 4, and LU 6, while moderate levels were recorded in LU 3 and LU 5. The relatively low Exch. Mg content in these land units is likely associated not only with acidic soil pH but also with parent material and soil mineral composition. Low magnesium levels in soils may result from several factors related to soil properties, environmental conditions, and soil management practices. Common causes include sandy or acidic soils, nutrient leaching due to high rainfall, and competition with other cations in the soil [37]. High magnesium content is typically found in primary minerals such as dolomite, magnesite, brucite, carnallite, talc, and olivine [14]. In addition, exchangeable Mg levels are influenced by soil pH (H^+ activity), calcium concentration, and lime content [38].

The analysis of available Fe at the research site showed that all six land units were classified in the very low category. Iron (Fe) is an essential micronutrient that plays a critical role in chlorophyll synthesis, energy transfer, and functions as a component of various enzymes and proteins. It is also involved in plant respiration and key metabolic processes, including nitrogen fixation. Although Fe is required only in small amounts, its deficiency can limit plant growth and physiological functions. According to [39], micronutrients are needed in relatively low concentrations; however, excessive levels may cause toxicity, degrade soil quality, and adversely affect plant growth and productivity. A comparison of exchangeable cation levels (K, Ca, Mg, and Fe) among land units in the study area is presented in **Figure 3**.

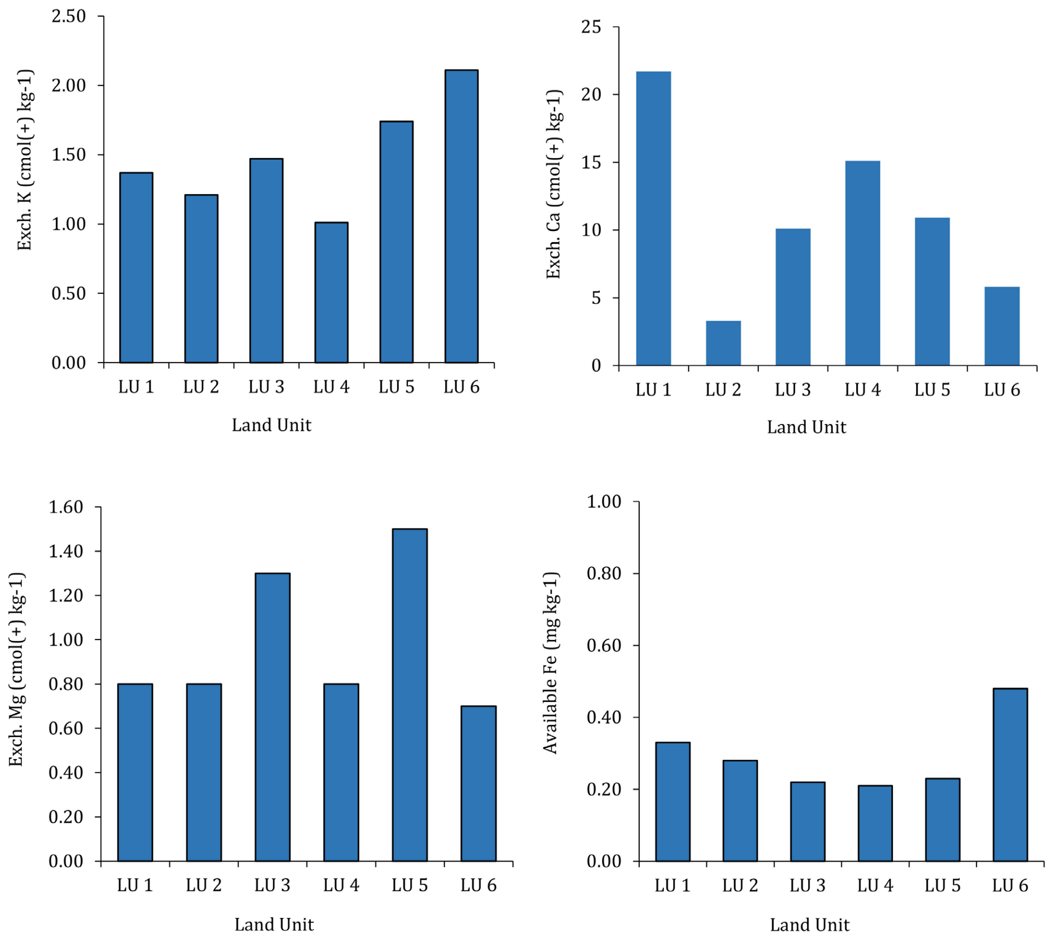

Figure 3. Comparison of exchangeable K, Ca, Mg, and available Fe across land units in the Inceptisols of Aceh Besar.

Figure 3 shows that, except for available Fe, the exchangeable cations K, Ca, and Mg in the patchouli development area are at levels sufficient to meet crop requirements, as they are above the low threshold or minimum critical limit. This indicates that potassium, calcium, and magnesium are not limiting factors for patchouli cultivation in the study area. Potassium (K), calcium (Ca), and magnesium (Mg) play essential roles in the growth and development of patchouli. Potassium functions in plant metabolism, water and nutrient transport, and contributes to improving the quality of patchouli oil. Calcium is crucial for cell wall strength and tissue development, and it also facilitates the uptake of other nutrients. Potassium is involved in various enzymatic reactions vital for plant metabolism, including protein and carbohydrate synthesis [40]. It also supports the transport of water and nutrients throughout the plant, ensuring the availability of essential materials for growth. Adequate potassium supply has been shown to increase biomass production (herbage yield) and enhance the quality of patchouli oil [2] [13].

Calcium (Ca) plays several important roles in patchouli plants, particularly in cell wall formation, stem growth, and seed development. Calcium deficiency may result in symptoms such as leaf scorch, leaf drop, and general defoliation [41]. Adequate calcium supply can enhance patchouli yield quality, including the quality of the essential oil produced. Conversely, calcium deficiency may cause structural damage to leaves and stems, as well as increased leaf abscission [13]. Magnesium (Mg) is a key component of chlorophyll and is directly involved in photosynthesis [41]. In patchouli plants, Mg is essential for oil formation. As a central component of chlorophyll, magnesium supports photosynthesis, directly affecting biomass and secondary metabolite production. Additionally, Mg is involved in energy and protein metabolism and may contribute to increased patchouli oil content. Magnesium deficiency may lead to leaf yellowing, chlorosis, and leaf drop in patchouli plants. However, this assumption requires further investigation, as research findings on magnesium nutrition in patchouli remain limited.

The low levels of available Fe observed in the study area are likely associated with the relatively high calcium content. Iron (Fe) commonly predominates in acidic, low-lime soils, whereas Fe deficiency frequently occurs in calcareous soils. The optimal concentration of iron (Fe) in soil solution considered adequate for most crops' ranges from 2.5 to 10 ppm ($mg \cdot kg^{-1}$) [42], while the values recorded at the study site were below 1.0 ppm ($mg \cdot kg^{-1}$) (**Table 4**). This finding indicates that Fe may act as a limiting micronutrient for patchouli growth in the area.

As is widely recognized, iron plays a crucial role in the growth and development of patchouli plants. It is involved in chlorophyll synthesis, energy transfer, and constitutes an essential component of various enzymes and proteins that function in plant respiration and metabolism, including nitrogen fixation. Iron deficiency in patchouli may result in chlorosis (yellowing of young leaves), stunted growth, and reduced essential oil production. Therefore, adequate Fe availability is essential to ensure optimal plant growth and high-quality patchouli oil production. The low available Fe content identified in the study area should thus receive particular attention in nutrient management strategies for patchouli cultivation.

3.2. Cation Selectivity and DRIS Analysis

Cation selectivity in soil solution refers to the tendency of soil particles to retain certain cations over others preferentially. This preference is influenced by several factors, including the charge and ionic radius of the cations, the characteristics of soil cation exchange sites, and the presence of competing ions in the soil solution. The DRIS (Diagnosis and Recommendation Integrated System) analysis evaluates interactions among nutrient cations such as K, Ca, and Mg in soils, relying on nutrient ratios, particularly those involving calcium (Ca), magnesium (Mg), and potassium (K). Although DRIS is commonly applied to diagnose plant nutritional status through leaf analysis, it can also be used to assess soil cation balance, as these ratios are important indicators of soil fertility status. Cation ratios of K:Ca, K:Mg, and Ca:Mg can be evaluated to better understand soil nutrient balance, as shown in **Table 5**.

Table 5. Molar ratios of soil cations K, Ca, and Mg in each land unit of the Inceptisols in Aceh Besar.

LU	Slope (%)	Land use type	Ca:K	K:Mg	Ca:Mg
1	0 - 8	Secondary forest (Sf)	15.8 (16:1)	1.71 (2:1)	27.1 (27:1)
2	0 - 8	Dryland farming (Df)	2.73 (3:1)	1.51 (2:1)	4.13 (4:1)
3	0 - 8	Shrubs (Sb)	6.87 (7:1)	1.13 (1:1)	7.77 (8:1)
4	8 - 15	Secondary forest (Sf)	15.0 (15:1)	1.26 (1:1)	18.9 (19:1)
5	8 - 15	Dryland farming (Df)	6.26 (6:1)	1.16 (1:1)	7.27 (7:1)
6	8 - 15	Shrubs (Sb)	2.75 (3:1)	3.01 (3:1)	8.29 (8:1)

Based on the calculated Ca:K, K:Mg, and Ca:Mg ratios presented in **Table 5**, the values vary considerably among land units. The Ca: K ranges from 3:1 to 16:1, indicating substantial variations in the selectivity of Ca and K on the soil exchange complex. The Ca:K is an important indicator for assessing the balance and availability of calcium and potassium in soil for crop uptake, including patchouli. Understanding this ratio is essential for appropriate soil fertility management and fertilizer recommendations to support optimal plant growth. The ideal Ca:K in soil generally ranges from 5:1 to 10:1, although this may vary depending on soil type and crop requirements [43]. This ratio reflects the relative proportion of calcium and potassium occupying the soil cation exchange complex. In terms of base saturation, some researchers suggest that an ideal soil condition is characterized by approximately 65% of the cation exchange capacity (CEC) occupied by calcium, 10% by magnesium, and 5% by potassium [44]. The calculated Ca to K ratio for the Inceptisols in the study area indicates that only two land units, LU 3 and LU 5, fall within the ideal range, with ratios of 7:1 and 6:1, respectively. This finding indicates that most soils in the study area may face imbalances in Ca and Mg availability due to potential competition among cations at exchange sites [16].

The ideal K: Mg ratio in soil depends on soil type and crop species, but it generally falls within the range of 1:1 to 2:1 and is considered suitable for most crops. Ratios that are excessively high or low in either K or Mg may lead to nutrient imbalance, interfere with the uptake of other elements, and consequently affect plant growth [44]. The calculated values presented in **Table 5** indicate that the K:Mg ranges from 1.13 to 3.01 (approximately 1:1 to 3:1). This indicates that most soils in the study area are chemically suitable for patchouli cultivation, except LU 6, showing a K:Mg ratio of 3:1. This condition implies that competition between K and Mg at exchange sites may occur in LU 6, potentially affecting magnesium uptake by patchouli plants. The Ca: Mg, based on the data presented in **Table 5**, ranges from 4:1 to 27:1, indicating substantial variability among land units. The ideal Ca: Mg is generally considered to be between 5:1 and 10:1 for most crops

[45]. Ratios that are excessively high or low in either Ca or Mg may lead to nutrient imbalance, interfere with the uptake of other elements, and adversely affect plant growth.

Based on the findings of this study, potential competition between Ca and Mg is likely to occur in the Inceptisols of LU 1, LU 2, and LU 4. Therefore, these land units require particular attention in fertilizer management to ensure balanced nutrient availability for optimal patchouli growth.

3.3. Nutrient Sufficiency and Requirements for Patchouli Cultivation

Patchouli requires essential nutrients such as nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) to support optimal growth and essential oil production. Commonly used fertilizers include urea, SP-36, and KCl. Fertilizer application rates may vary; however, a typical basal recommendation includes 200 kg urea (equivalent to 90 kg N), 200 kg SP-36 (72 kg P), and 150 kg KCl (90 kg K) per hectare [46]. In addition, dolomite can be applied to supply Ca and Mg, particularly in acidic soils (pH < 5.5). The incorporation of farmyard manure at rates of 10 - 20 $t \cdot ha^{-1}$ is also recommended to improve soil fertility. Higher urea application rates of 250, 280, and 560 $kg \cdot ha^{-1}$ have been reported to increase patchouli yield, although maximum production levels have not yet been achieved [1]. Micronutrients, including Fe, may be supplied in liquid fertilizer form at a concentration of 20 mL per liter of water.

Table 6. Average availability of macronutrients (N, P, K, Ca, and Mg) and the micronutrient Fe per hectare in each land unit of the Inceptisols in Aceh Besar.

LU	Slope (%)	Land use type	N	P	K	Ca	Mg	Fe
			($kg \cdot ha^{-1}$)					
1	0 - 8	Secondary forest (Sf)	118	10.5	1069	8680	19.2	0.66
2	0 - 8	Dryland farming (Df)	40	7.68	944	1320	19.2	0.56
3	0 - 8	Shrubs (Sb)	42	6.24	1147	4040	31.2	0.44
4	8 - 15	Secondary forest (Sf)	62	9.64	788	6040	19.2	0.42
5	8 - 15	Dryland farming (Df)	42	10.1	1357	4360	36.0	0.46
6	8 - 15	Shrubs (Sb)	58	7.90	1646	2320	16.8	0.96

Table 6 shows that the available contents of N, P, K, Ca, Mg, and Fe at the study site vary considerably among land units. The amounts of each nutrient per hectare in available form in the Inceptisols range as follows: 40 - 118 kg N; 6.24 - 10.5 kg P; 788 - 1646 kg K; 1320 - 8680 kg Ca; and 0.42 - 0.96 kg Fe. Based on the nutrient requirements for patchouli, namely 90 kg N, 72 kg P, 90 kg K, 434 kg Ca, 260 kg Mg, and 5 kg Fe per hectare, it is evident that nitrogen, except in LU 1, phosphorus, magnesium, and iron remain deficient in the patchouli cultivation area. In contrast, potassium and calcium are present in sufficient amounts (**Table 7**).

Table 7. Estimated requirements of macronutrients (N, P, K, Ca, and Mg) and the micronutrient Fe per hectare in each land unit of the Inceptisols in Aceh Besar*).

LU	Slope (%)	Land use type	N	P	K	Ca	Mg	Fe
			------------------------ ($kg \cdot ha^{-1}$)-------------------					
1	0 - 8	Secondary forest (Sf)	**	61.5	**	**	240.8	4.34
2	0 - 8	Dryland farming (Df)	50	64.3	**	**	240.8	4.44
3	0 - 8	Shrubs (Sb)	48	65.8	**	**	228.8	4.56
4	8 - 15	Secondary forest (Sf)	28	62.4	**	**	240.8	4.58
5	8 - 15	Dryland farming (Df)	48	61.9	**	**	224.0	4.54
6	8 - 15	Shrubs (Sb)	32	64.1	**	**	243.2	4.04

*) Standard Nutrient Requirements: [90 kg N + 72 kg P + 90 kg K + 434 kg Ca + 260 kg Mg]/ha + 5 kg Fe/ha or equal 200 kg/ha Urea, 200 kg/ha SP-36, 150 kg/ha KCl + 2-ton Dolomite [Ca, Mg $(CO_3)_2$] + 13.6 $FeSO_4$/ha. ** sufficient.

According to these calculations, nutrient deficiencies in the study area should be corrected through the application of additional fertilizers at the following rates: 28 - 50 kg $N \cdot ha^{-1}$; 61.6 - 65.8 kg $P \cdot ha^{-1}$; 228.8 - 243.2 kg $Mg \cdot ha^{-1}$; and 4.04 - 4.58 kg $Fe \cdot ha^{-1}$. Based on previous studies, recommended fertilizer sources include urea (45% N) for nitrogen, SP-36 for phosphorus, dolomite for magnesium, and $FeSO_4$ for iron [47]. Micronutrients may also be applied in liquid form at a concentration of 10 mL per liter of water [48]. It is recommended to prioritize N, P, Mg, and Fe inputs, combined with organic amendments and liming to improve soil pH, enhance nutrient availability, and sustain patchouli productivity on Inceptisols.

4. Conclusions

The chemical properties of the Inceptisols in the patchouli development area of Lhoong Sub-district, Aceh Besar Regency, indicate generally favorable soil fertility conditions. Most land units exhibit moderate to high soil organic carbon (2.27% - 6.40%), low to moderate total nitrogen (0.21% - 0.59%), high exchangeable potassium (1.01 - 2.11 cmol(+)$\cdot kg^{-1}$), and moderate to very high exchangeable calcium (5.80 - 21.7 cmol(+)$\cdot kg^{-1}$), indicating overall suitable for patchouli cultivation. However, acidic pH and deficiencies in essential nutrients limit soil performance. Wide variations in cation selectivity ratios of Ca:K (3:1 to 16:1), K:Mg (1:1 to 3:1), and Ca:Mg (4:1 to 27:1) indicate imbalanced nutrient interactions and competition among base cations at exchange sites, potentially limiting nutrient uptake in patchouli. Based on nutrient balance evaluation, fertilizer supplementation is required to address these deficiencies, with estimated application rates of 28 - 50 kg $N \cdot ha^{-1}$, 61.6 - 65.8 kg $P \cdot ha^{-1}$, 228.8 - 243.2 kg $Mg \cdot ha^{-1}$, and 4.04 - 4.58 kg $Fe \cdot ha^{-1}$. These findings highlight the importance of site-specific nutrient management to improve soil fertility and enhance patchouli productivity through balanced fertilizer application and the addition of organic amendments and lime.

Authors' Contributions

ZZ designed the experiment, conducted the field experiment, and drafted. SS conceptualized the study, collected the research data, and edited the manuscript. HH edited the data and interpretation, YJ created the figure design, and NF analyzed the field data. All authors read and approved the final manuscript.

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Conflicts of Interest

The authors declare that there is no conflict of interest.

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